

P 422099

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**University of Hawaii**

**Final Technical Report**

**Submitted to the**

**National Aeronautics and Space Administration**

**Grant No. NAG5-4227**

**"High Angular Resolution Observations of  
Protoplanetary Disks with Adaptive Optics"**

**May 1, 1997 to April 30, 1999**

**Submitted by**

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Significant results were obtained and published in the literature. The first optical detection of a circumbinary disk (a large disk surrounding both stars in a binary system) was reported in the ApJ (C. Roddier et al 1996, ApJ, 463, 326-335) confirming observations made at about the same time at millimetric wavelengths. The size and inclination of this disk (detected around the young binary star GG Tau) were found to be consistent with millimetric observations. Evidence was found for a cavity inside the disk as theory predicts from dust clearing by the stellar companion.

High angular resolution images of the young star HL Tau were obtained in the infrared (L. M. Close et al. 1997, ApJ 478, 766-777) and combined with visible light images obtained with the Hubble Space Telescope (HST). In the HST images the central star is totally hidden in a thick circumstellar nebula. Our infrared observations revealed the central star, allowing us to precisely locate its position inside the nebula. Evidence was found for an active accretion disk surrounding the central star, the properties of which were modeled. On each side of the disk, bipolar cavities were also detected and observed at three epochs over a two year period. The northern cavity was found for an expansion with a velocity up to 30 km/s. The nebula around HL Tau is believed to be similar to the original solar nebula, when the sun was only 100,000 year old.

A detailed analysis of the dust properties and scattering geometry of another circumbinary disk was published (Close et al. 1998, ApJ, 499, 883-888). This paper looked in detail at the morphology and spectral character of the 500 AU circumbinary disk discovered around the T Tauri binary UY Aur. It was discovered that (like the circumbinary GG Tau) the brightest side of the circumbinary disk is brightened due to forward scattering. Also we were able to show that the dust grains in these disks have a maximum dust grain radius of  $\sim 0.6$  microns. This appears to be true for both the GG Tau and UY Aur circumbinary disks. This suggests that the dust probed by the NIR AO imaging is close to that typical of the ISM.

This finding of smaller grains is in disagreement with the dust sizes inferred from mm studies. Dust sizes inferred from the mm albedo of dust grains tend to suggest sizes close to mm sizes. However, a possible solution to this apparent contradiction is that the NIR AO studies image scattered light off the top surface of the disks, which by definition have low optical depths. However, the mm studies penetrate to the very midplane (high optical opacity) of the disks where larger grains may be forming rapidly (as the process of grain sedimentation may be occurring). Clearly more observations will be required to try and confirm if there is a gradient in dust grain size as one passes from the optically thick disk midplane to the optically thin disk surface. If grain sedimentation has already started to occur it might suggest the start of the planet formation process.

To further probe the interesting properties of these circumbinary disks we (for the first time) attempted resolved imaging polarimetry of a circumstellar disk. This is not an easy feat since it requires one to image the faint (one million times fainter at separations of only 3") extended emission of the disk. While this is difficult enough it is made even harder by the polarimetric constraint that the PSF flux must remain constant to this level to measure the differences between images as viewed through the different polarimetric angles. However, the extremely stable PSF produced by our new 36 element AO system (Hokupa'a) at CFHT was able to produce 4x30 min. exposures to this level of stability. At this point Laird Close and graduate student Dan Potter attempted to define new techniques to obtain high accuracy polarimetry from AO images of faint circumstellar disks. Dan Potter did define a new technique which allowed this resolved polarimetry map to be obtained of a resolved circumstellar disk.

Dan Potter modeled this disk with an Mie scattering code that was developed in Close et al. 1998a. With this code we modeled the expected behavior of polarization amplitude with scattering angle around the disk. We found that based on the grain properties found in Close et al. 1998a it appeared that peak polarizations should occur at 90 degree scattering angles with minima in the front and back sides of the disk. We did in fact observe such a dependence of the polarization.

Moreover, based on this dependence we could for the first time conclude that the faint NIR nebulosity around this binary was indeed dust confined to a planar geometry, just what we expect from a dusty disk. This work is in press (Potter et al. 1999, ApJ).

Other highlights include very deep 10 and 20 micron imaging of the circumbinary disk around UY Aur. This data obtained from the MIRAC2 camera at IRTF and UKIRT telescopes. The IRTF data has now been reduced while the UKIRT data (just taken) is being worked on currently.

We have also just published the first wide field AO survey of the Orion Trapezium cluster with M. Simon and T. Beck (SUNY Stonybrook). This landmark paper goes into great detail of the photometric, binarity, and luminosity function of the 295 stars located within the inner 6 square arc min. of the Trapezium cluster. New techniques were investigated in how to analyze wide field AO data. In the end we found a combination of spatially variable PSF fitting photometry was best able to obtain photometry to ~10% in the crowded cluster core. We also found that despite our deep, high-resolution images there are very few faint new sources discovered in the cluster. We also found that the cluster age is close to one million years in agreement with other studies. As well we concluded that there is no significant binary excess in this OB cluster. This is in agreement with other studies as well. This work will appear in the June AJ as Simon, Close & Beck (1999).

Our Trapezium results continue the puzzling trend that low density clusters like the T-association in Taurus has a binary excess while in high density clusters (like Trapezium) there is no excess of binary systems compared to the local field. To further analyze the dependence of binarity on cluster density we (Beck, Close & Simon) have now obtained images of the inner 4 square arc min of the Orion cluster NGC 2024 last fall at CFHT with the PUEO AO system. Data reduction is underway and we hope to have another cluster paper on NGC 2024 published soon.

Major advancements were made in other areas of the project. A complete review of disk imaging in the NIR/Optical with AO/HST was published in the refereed Protostars and Planets IV proceedings. This chapter gives a complete outline of all disk systems imaged and detected to date. The invited chapter authors were M. McCaughrean, K. Stapelfeldt & L. Close.

Progress on a Herbig Ae/Be star survey was made as well as the T Tauri star survey. Disk detections have been rare however and we are looking forward to extending our survey with the new generation 8m telescopes with AO system (such as Hokupa'a on the GEMINI telescope).

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## **Publications:**

Adaptive Optics Imaging of GG Tau: optical detection of the circumbinary ring (C. Roddier et al.) ApJ. **463**, 336-343 (1996).

Adaptive optics 0".2 resolution infrared images of HL Tauri: direct images of an active accretion disk around a protostar (L.M. Close et al.) ApJ. **478**, 766-777 (1997).

Adaptive Optics Infrared Imaging-Polarimetry and Optical HST Imaging of Hubble's Variable Nebula (R Mon / NGC 2261): A Close Look at a Very Young Active Herbig Ae/Be star (L.M. Close et al.) ApJ **489**, 210-221 (1997).

Adaptive Optics Imaging of the Circumbinary Disk Around The T Tauri Binary UY Aur: Estimates of the binary Mass and Circumbinary Dust Grain Size Distribution (L.M. Close et al.) ApJ **499**, 883-888 (1998)

Adaptive Optics Survey of the Trapezium star cluster (M. Simon, L.M. Close & T. Beck) AJ in press (1999)

Adaptive Optics (L.M. Close) 1999 Yearbook of Science and Technology, McGraw Hill NY.

High-Resolution Optical and Near-Infrared Imaging of Young Circumstellar Disks (M. McCaughrean, K. Stapelfeldt, & L.M. Close) Protostars and Planets IV, Santa Barbara, July 6-13, 1998

### **Conference Proceedings:**

A Model of scattering from Dust in Proto-planetary Disks applied to 0.1" resolution U. of Hawaii Adaptive Optics Images of the disks around Young Stars (D. Potter, L.M. Close, & F. Roddier) 1998, BAAS **191**, #05.03

High-Resolution Imaging of Young Circumstellar disks (L.M. Close, K. Stapelfeldt) invited review talk, Protostars and protoplanets IV, Santa Barbara, July 13, 1998

Astronomical Results from the University of Hawaii Adaptive Optics Program: Astronomical Problems Well Suited to Adaptive Optics Techniques, L.M. Close, Roddier, F., Roddier, C., Graves, J.E., & Northcott, M. 1998, Proc. SPIE **3353**

The Binary Fraction in Different star forming Regions, Duchene, G., Bouvier J., Simon, T., Close, L.M., & Eisloffel, J. CFHT Users Meeting 1998, Quebec City.

The Binary Fraction in Different star forming Regions, Bouvier, J., Duchene, G., Simon, T., Close, L.M., & Eisloffel, J. Protostars & Planets IV, 1998 July 6-13th Santa Barbara.

Low-mass stars in young open clusters: a deep near-infrared adaptive optics binary survey G. Duchene, J. Bouvier, T. Simon, L. Close, & J. Eisloffel, 1998 ESO/OSA Astronomical Adaptive Optics Sept. 6-11th Sonthofen, Germany

Adaptive Optics Imaging of Circumstellar Disks and low Mass Companions around Young Stars Close, L.M., Roddier, F., Potter, D., Roddier C., Graves, J.E., & Northcott, M. 1998 ESO/OSA Astronomical Adaptive Optics Sept. 6-11th Sonthofen, Germany

Four-years of observations of T Tauri with Adaptive Optics Roddier, C. Roddier, F., Graves J.E., Northcott, M.J., Close, L.M., Tokunaga, A., Surace, J., & Veran, J.P 1998 ESO/OSA Astronomical Adaptive Optics Sept. 6-11th Sonthofen, Germany

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE December 6, 1999		3. REPORT TYPE AND DATES COVERED May 1 1997 - April 30, 1999	
4. TITLE AND SUBTITLE High Angular Resolution Observations of Protoplanetary Disks with Adaptive Optics				5. FUNDING NUMBERS NAG5-4227	
6. AUTHORS Francois Roddier					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Hawaii Institute for Astronomy 2680 Woodlawn Dr. Honolulu, HI 96822				8. PERFORMING ORGANIZATION REPORT NUMBER 6-54638	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Greenbelt, MD 20771				10. SPONSORING/MONITORING AGENCY REPORT NUMBER NAG5-4227	
11. SUPPLEMENTARY NOTES					
12a. DISTRIBUTION/AVAILABILITY STATEMENT				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  Significant results were obtained and published in the literature. The first optical detection of a circumbinary disk was reported in the ApJ at millimetric wavelengths. The size and inclination of this disk were found to be consistent with millimetric observations. Evidence was found for a cavity inside the disk as theory predicts from dust clearing by the stellar companion.					
14. SUBJECT TERMS circumbinary disk, ApJ				15. NUMBER OF PAGES 4 pages	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT		